HYPERVELOCITY COMBUSTION SPRAYED

PROTECTIVE COATINGS

AN ASSESSMENT OF THE TECHNOLOGY

N0001489J3163

Final Report

Submitted to:

Naval Sea Systems Command
David Taylor Naval Ship R&D Center
Annapolis, MD 21402
Attn: Jean Montermorano
Code 2803

by

Prof. Herbert Herman
Thermal Spray Laboratory
Dept. of Materials Science & Engineering
State University of New York
Stony Brook, NY 11794-2275

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A Proposal for Continuation of Research

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Proposed Budget: $46,850

Proposed Duration: One Year

Proposed Starting Date: 1 July 1990

Abstract

HVOF technology is being evaluated in this NAVSEA - supported program. A number of materials are being HVOF sprayed, characterized and tested. Preliminary results point to a dramatic enhancement of properties using HVOF technology vs. traditional plasma spraying. It is proposed to offer an extension of HVOF in this proposal for renewal involving a test of the concept that the fatigue life of a machine element can be extended by HVOF coating.

Introduction

High Velocity Oxy-Fuel (HVOF) spraying emerged in 1982 with the introduction of the Browning Jet Kote System. HVOF involves the combustion of an oxygen-fuel mixture to achieve high gas velocities which are used to heat an accelerate a powdered feedstock to produce a coating. During the last several years other HVOF systems have been introduced, namely Metco's Diamond Jet, Sulzer's CDS, Miller's Top Gun, and Eutectic's High Energy Combustion Spray. Although all of these systems fall under the classification of HVOF systems, each is essentially different, and, therefore, each must be studied independently to determine if it meets the needs of the required applications.

The goal of this project is to evaluate the coatings produced by these HVOF systems relative to various marine-based applications. This proposal will first outline the evaluation methods that are being used and some preliminary results will be presented. Also to be discussed is the possibility of HVOF-induced enhancement of a machine element's fatigue life.

The Systems

Jet Kote (JK) is the oldest of the HVOF systems on the market. The current Jet Kote system is similar to the earlier ones, with changes mainly in internal gun modifications. Fuel and oxygen are mixed and combusted in a chamber, the hot high velocity combusted gas being transported through four smaller chambers that bend the flow by 90° and then converging on a central axis into which powder is injected. The gases are then constrained by a straight bore nozzle where the particles are heated and accelerated. A cross-section of the Jet Kote gun is shown in Figure 1.

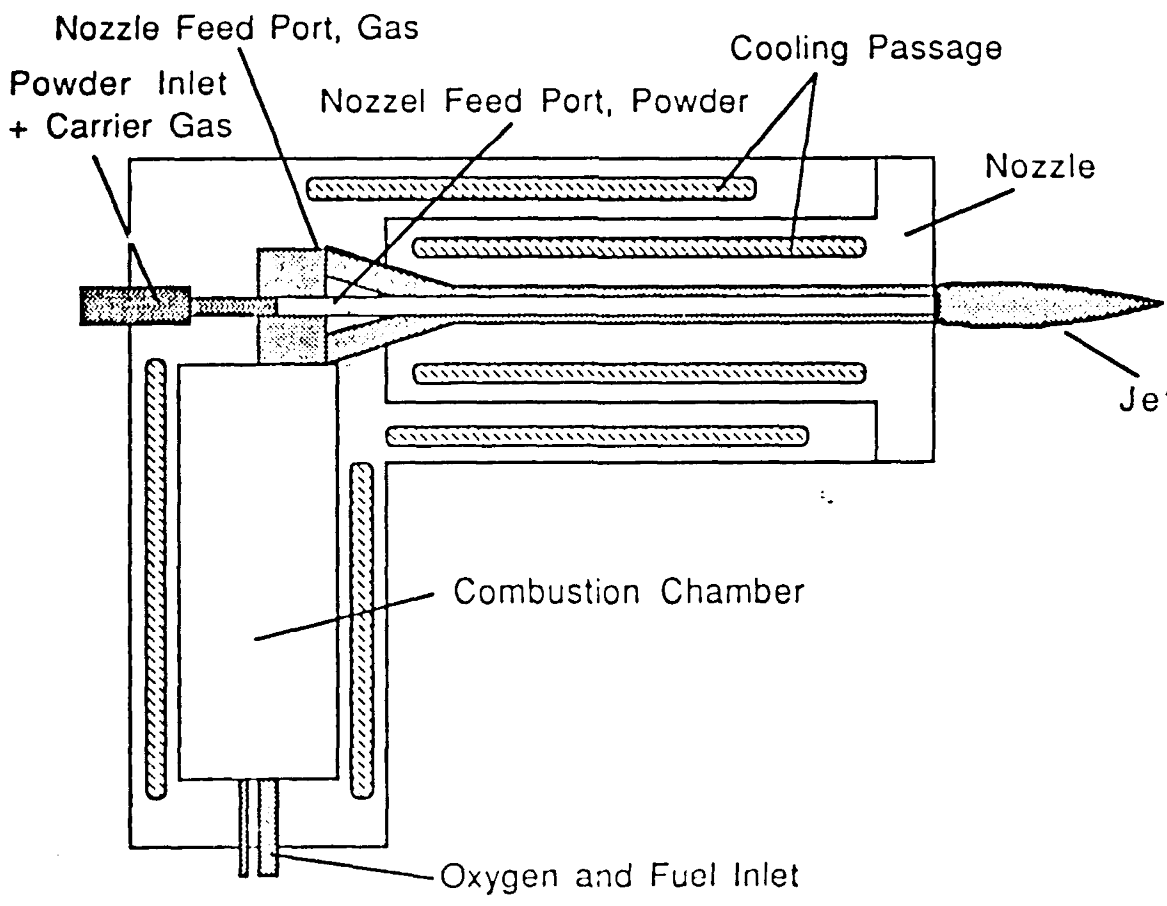

Figure 1. A cross-section of the Jet Kote Gun

Sulzer Plasma Technik's CDS gun feeds the uncombusted fuel and oxygen gases into a small combustion chamber at the entry of the nozzle. The fuel and oxygen are fed concentrically around the axis into which the carrier gas is injected. The burning gases pass down the nozzle, accelerating and heating the particles. A cross-section of the CDS gun in shown in Figure 2.

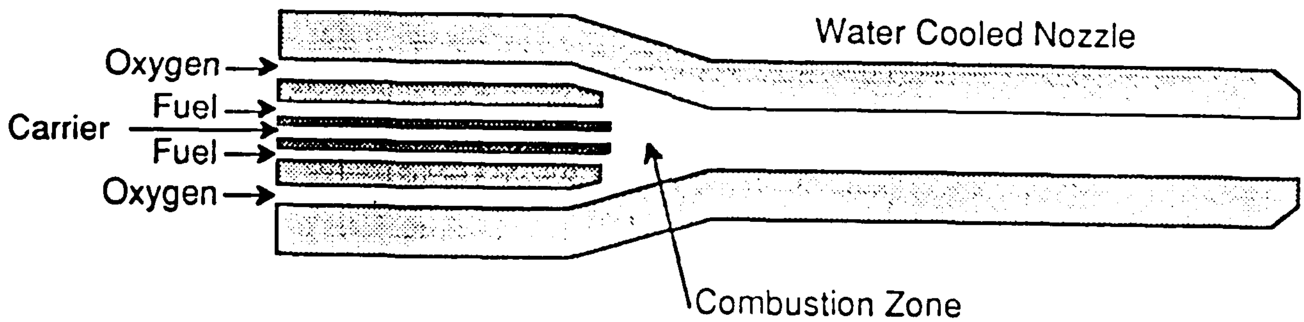

Figure 2. Sulzer Plasma Technik's CDS Gun.

Metco-Perkin Elmer's Diamond Jet (DJ) is somewhat different from the other systems in that there is no nozzle or water cooling. The combustion gases are premixed prior to ignition outside of the gun. The gun parts are cooled with compressed air from two sources. Air flows over the powder feed-tube for cooling, this air being allowed to mix with the combustion and the carrier gases. Air is also injected between the flame and an outer cap to cool the cap and to constrain the flame. A cross-section of the DJ gun is shown in Figure 3.

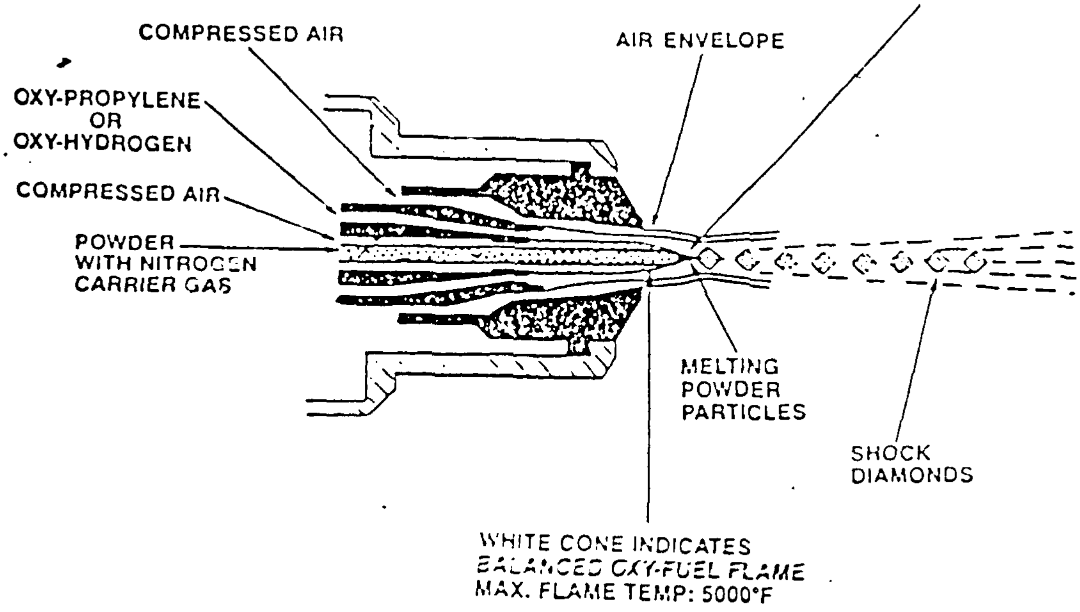

Figure 3. A cross-section of the Diamond Jet Gun

Materials

The materials to be evaluated for this program are: aluminum-bronze, Monel, Hastelloy C-276, tungsten carbide cobalt(WC/Co), alumina-titania, and Metco 143, a blend of zirconia, yttria, and titania. Not all of these materials have been developed as commercial coatings for all of the spray systems. For the JK system, WC/Co and Hastelloy C are established commercial coating materials, whereas Monel is still classified as experimental. For the DJ gun, aluminum-bronze and WC/Co are commercial coatings. Sulzers Plasma Techniks supports WC/Co and Al_2O_3-TiO_2 (60/40 for the CDS systems.

Experimental Procedure

For coatings that are commercial products for the system to be examined, the manufacture's powder and spray parameters are being used to produce the coating for evaluation. If such is not

the case, optimization of powder feedstock and spray parameters is necessary before the coatings can be evaluated. Initial optimization in general, involves assessment of coating quality by determining deposition efficiency, optical microscopy, and hardness testing. Once the operating parameters are determined, the coatings are subjected to the following testing procedures:

Optical and scanning electron microscopy (SEM) of a coating cross-section to provide qualitative information on density, oxide content, and the degree of melting;

X-ray diffraction to determine the phases present in the coating and in the starting powder;

Profilometry to characterize the surface roughness of the as-sprayed coating;

Rockwell macrohardness and Vickers microhardness measurements;

Tensile adhesion testing (TAT) conforming to ASTM standard C633-59, is performed for a determination of the coating bond strength (Figure 4);

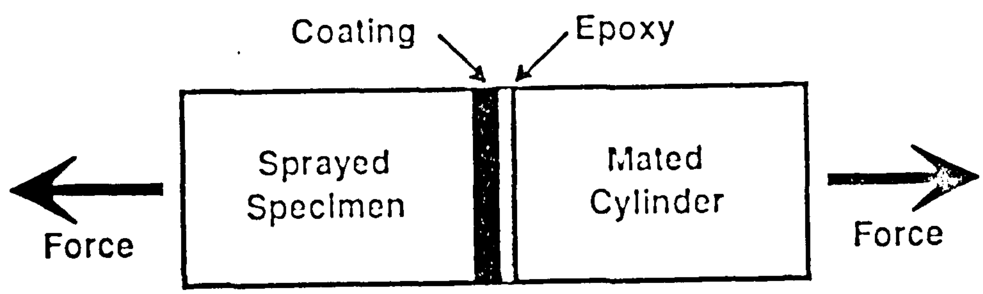

Figure 4. The Tensile Adhesion Test. A coating is sprayed on one cylinder and epoxied to a matching cylinder. The assembly is then subjected to a tensile load until failure occurs.

Wear Testing is performed on a Falex Model 6 Friction and Wear Testing Machine. A pin on disk test is employed as illustrated in Figure 5;

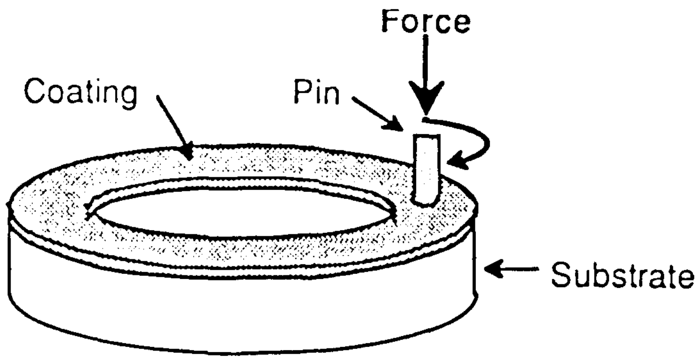

Figure 5. Pin-on-Disk Wear Testing. The coating to be tested is applied to the surface of the stationary disk. A load is applied to the pin which rotates against the coating surface.

Cavitation erosion testing is performed by subjecting the specimen, submerged in water (which can be distilled or a corrosive media), to cavitation produced by an ultrasonic vibratory horn oscillating at a frequency of 20 kHz and an amplitude of 40μm. A diagram of the cavitation setup is shown in Figure 6.

All materials, with the exception of aluminum-bronze, are sprayed on low carbon steel substrates of appropriate dimensions. The aluminum-bronze is sprayed onto bronze substrates, as specified by Military Standard 1687A(SH). All substrates are prepared by grit blasting and degreasing with acetone.

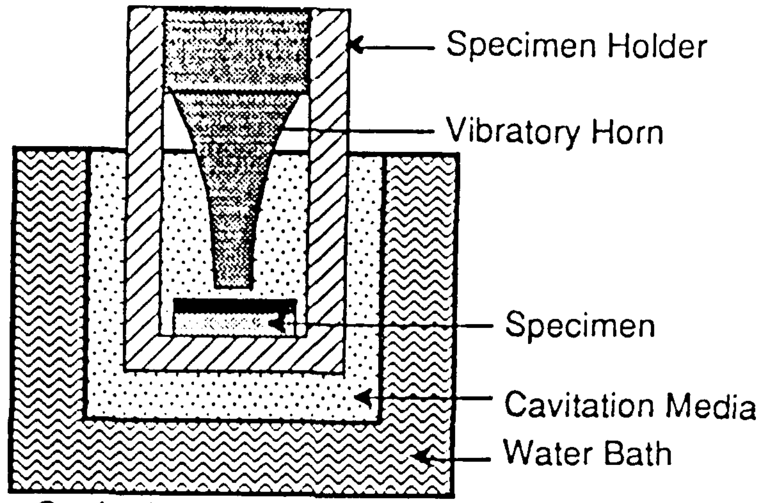

Figure 6. The Cavitation Erosion Test. The specimen is held 0.64mm from the horn tip while being cavitated in distilled water. A surrounding water bath is used to remove the heat generated during cavitation.

Results and Discussion

To date coatings have been produced with the JK system and, for a baseline comparison, the Metco 3MB plasma system at Stony Brook, the DJ at Metco-Perkin Elmer in Westbury N.Y. and the CDS system at Flame Spray Industries in Port Washington N.Y. Note, that in this section the results on the HVOF systems are compared with plasma sprayed coatings as a base-line.

Jet Kote: Hastelloy C-276

Coatings of Hastelloy C-276 have been sprayed with the JK system. When sprayed with the standard parameters provided by Cabot, the coatings contain a substantial number of partially melted particles as seen in the optical cross-section; Figure 7a. When the combustion gas flows are increased, all of the particles appear full melted in the cross-section; Figure 7b. While the

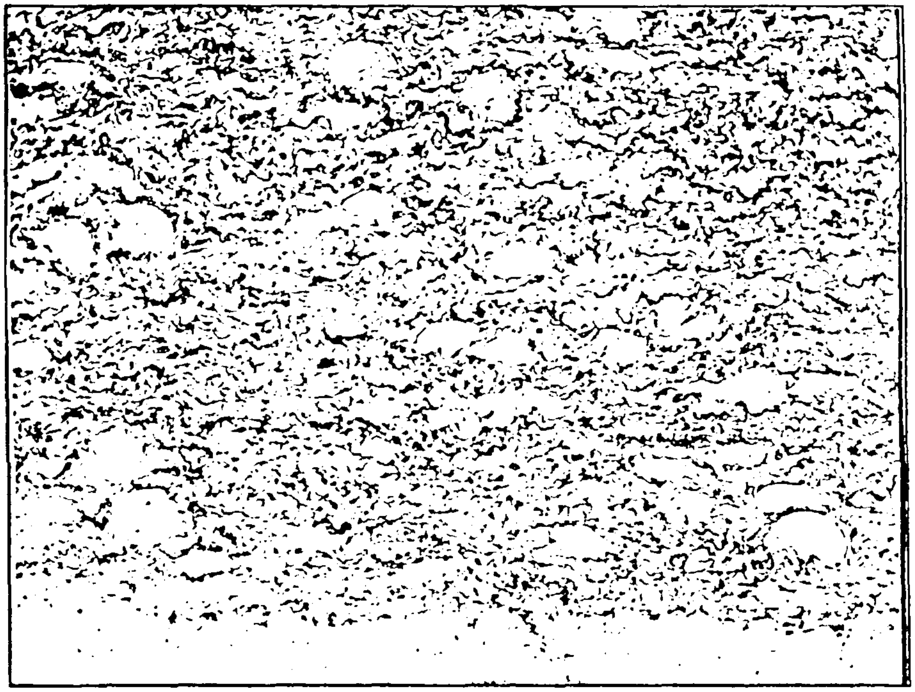

Figure 7a) Optical cross-section of Hastelloy C-276 coating sprayed with normal JK parameters (200X). Note the large number of unmelteds.

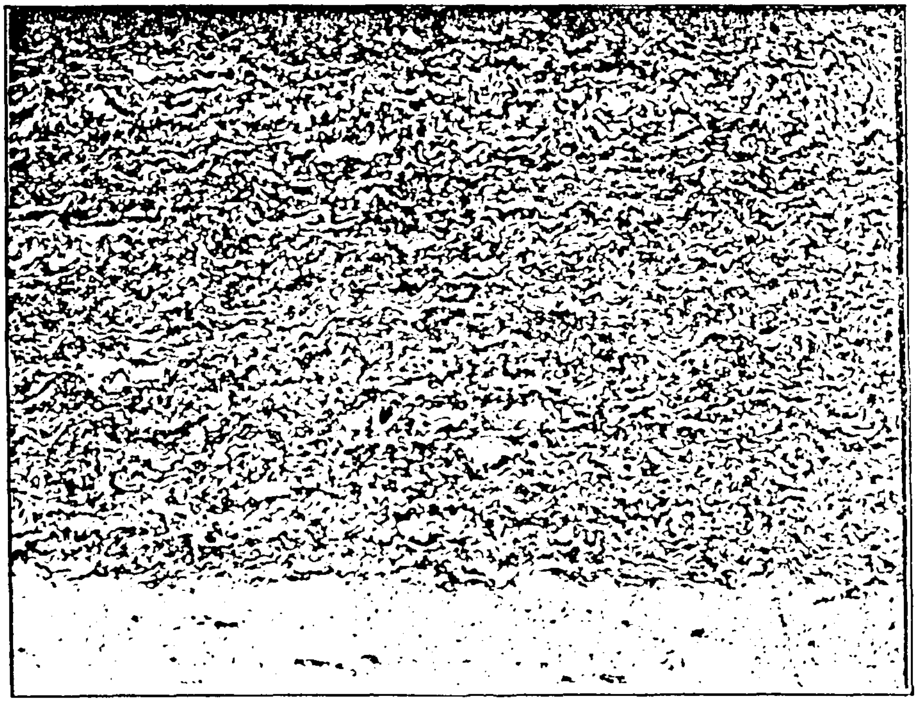

Figure 7b) Optical cross-section of Hastelloy C-276 coating sprayed with high JK parameters (200X). The coating apears fully melted.

fully melted cross-section is thought by the present investigators to be optimal, a contrary opinion was expressed by Stellite Coatings*, citing an "increased oxide content in the higher parameter coating" (sic.).

The hardness data for the Jet Kote and plasma sprayed C-276 coatings are given in Figure 8. It is seen that the increase in combustion gas flow results in a hardness increase from RH15N 81.5 to 85. This increased hardness is most likely due to both an increased oxide content and increased particle velocity resulting in higher coating densities and increased particle deformation on impact. All of the coatings produced with Jet Kote are harder that the plasma sprayed coating.

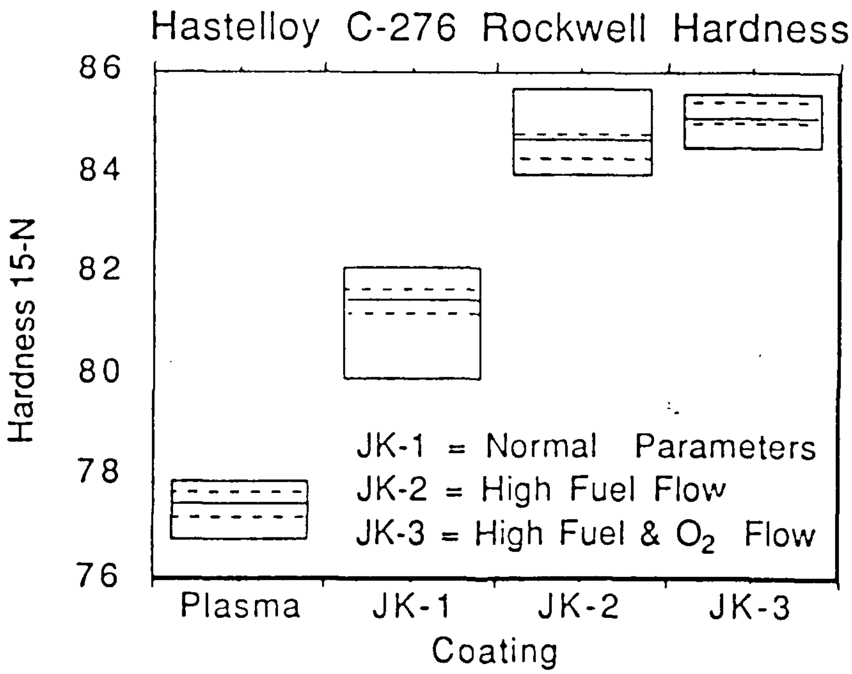

Figure 8. Hastelloy C-276 Hardness Data. The solid line is the sample mean, the dashed lines the standard deviations and the box encloses all data points.

*Private communication from David Lee, March 1990.

X-ray diffraction analysis indicates that the only phase present in the starting powder and the major phase present in the coating is a nickel-based FCC solid solution. The coating, however, also contains two oxide phases, $NiFe_2O_4$ and $(Cr,Fe_2)O_3$; Figure 9. Quantitative phases analysis is being conducted to determine the differences in oxide content with varying JK spray parameters.

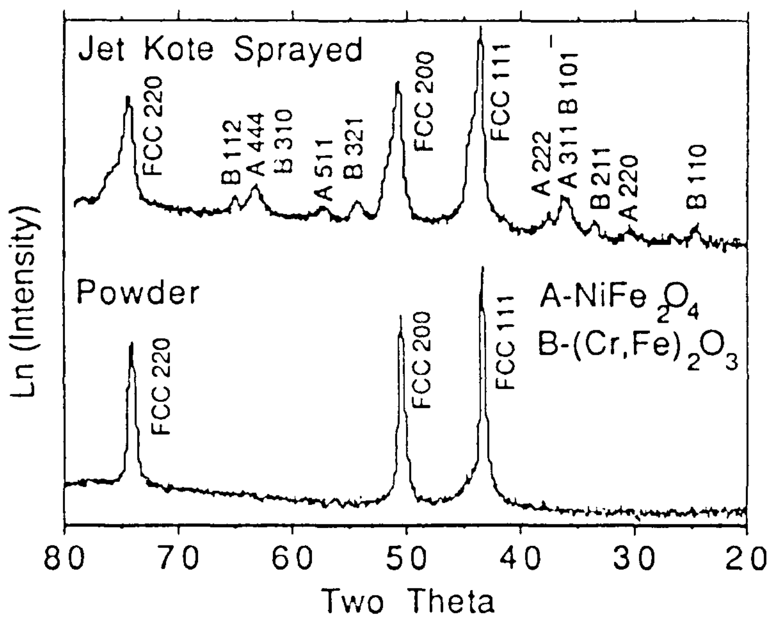

Figure 9. X-Ray Diffraction Pattern of Hastelloy C-276. The starting powder contains only a nickle based FFC solid solution. The Jet Kote sprayed coatings shows the formation of two oxide phases, $NiFe_2O_4$ and $(Cr,Fe)_2O_3$.

The cavitation-erosion responses of the two JK coatings and the plasma coating are plotted in Figure 10. The high parameter Jet Kote coating outperforms the standard coating; both JK coatings are more resistant than the same material sprayed by plasma. It should be noted that the higher rates of cavitation-erosion weight-loss imply a "coating of poorer quality".

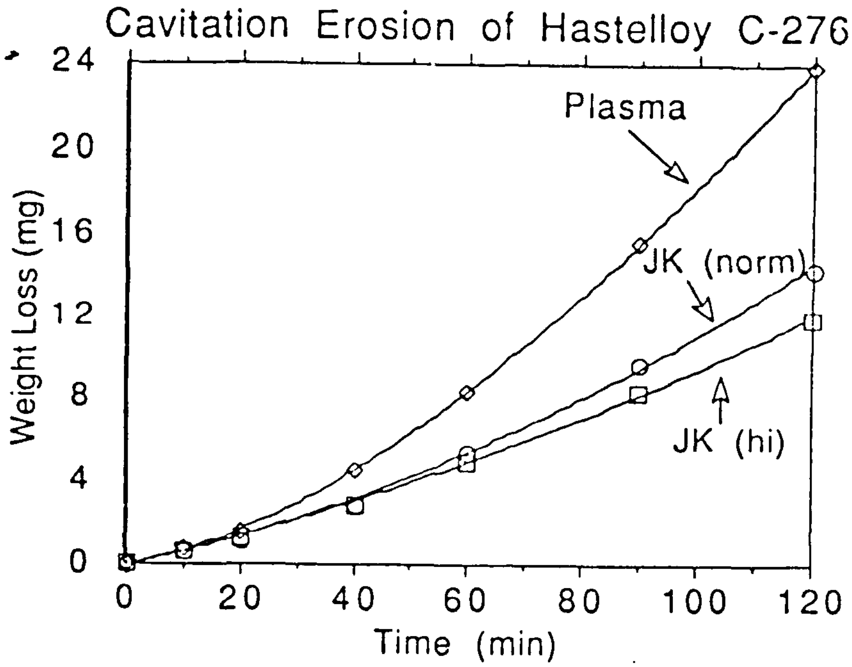

Figure 10. Cavitation Erosion Behavior of Hastelloy C-276 Coatings

To evaluate the level of interparticle bonding in the Hastelloy coatings, free-standing tensile specimens are being prepared. This information, when combined with the other test date, should rationalize the effects of the increased gas flows on the coating properties and microstructure, enabling a determination of the optimized coating.

Aluminum-Bronze

Aluminum-bronze coatings have been produced with JK, DJ, plasma, and electric arc. Macrohardness values for the coatings are plotted in Figure 11. The HVOF coatings have hardness values of 91-92 RH15T. The HVOF coatings are significantly harder than either the plasma or arc coatings with values of 83 and 78 RH15T, respectively. The effect of varying the JK operating parameters

does not produce the marked hardness changes seen with the Hastelloy coatings. This is due to the large particle size of the feedstock powder used for the JK coatings, 125-44 μm. Due the high mass of the particles, changes in particle velocity with gas flow changes will be smaller than those obtained with lighter particles.

Four sets of operating parameters are examined here; standard parameters (JK4), standard combustion flows with an increased carrier flow (JK5), increased fuel flow (JK6), and increased fuel and oxygen flows (JK7). Increasing only the carrier flow cools the flame and increases the particle's initial velocity, shortening the dwell time in the cooler flame. This results in a lower density coating and, therefore, a lower macrohardness. By increasing only the fuel flow, the heat of the flame can be increased without substantially increasing the gas velocity. This yields the best particle melting and was observed to produce the hardest coatings. Increasing both the fuel and oxygen gas flows increases the particle velocity, decreasing the particle's dwell-time in the higher energy flame. The fact that the high fuel flow coating is harder than the high fuel and oxygen coating indicates that the particles are too large. The larger particles have higher volume-to-surface ratio than smaller particle, so they are more difficult to melt and to accelerate. The observed results indicate that the powder particle size was too large and that a finer powder is called for. If the particle size is too small, melting will occur inside the nozzle, resulting in nozzle buildup and poor sprayability.

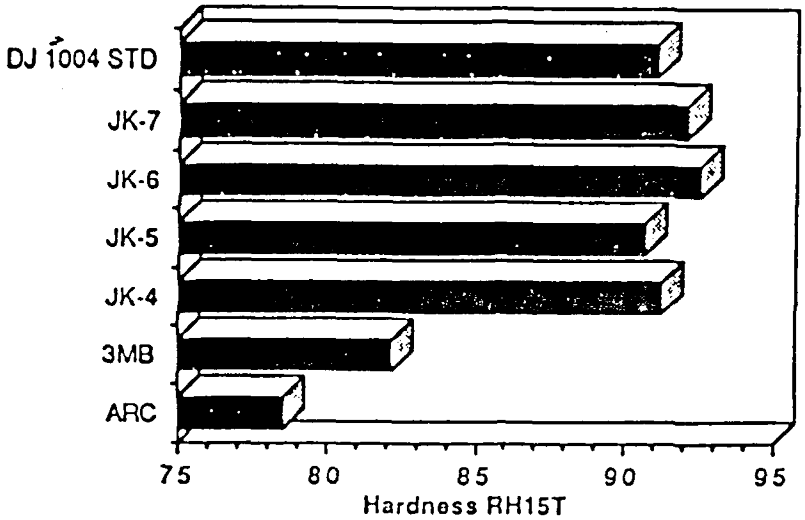

Figure 11. Macrohardness values for aluminum-bronze coatings produced by HVOF(JK,DJ), plasma and electric arc. The HVOF coatings are significantly harder than the plasma and arc coatings.

Despite the large particle size and the large number of unmelted particles, the JK sprayed aluminum-bronze coatings showed higher cavitation-erosion resistance when compared with a plasma spayed coating of the same powder; Figure 12. The plasma sprayed coating lost 40 mg during a 120 minute exposure. The JK coatings lost only 14 to 18 mg, depending on spray parameters. The high flow JK parameter coating showed an increased resistance to cavitation-erosion compared with the normal parameter coating. SEM micrographs of the cavitated surface of the JK coating show that the coating is made up of large unmelted particles bonded together with the smaller well-melted particles, Figure 13a. The cavitated plasma sprayed coating shown in Figure 13b is made up of fully-melted platelets, with some unmelted particles entrapped within the platelets. The unmelted particles in the plasma coating show a

size distribution, unlike the Jet Kote unmelteds, all of which are on the order of 120μm in diameter. This indicates that the plasma unmelteds are particles not being properly injected into the flame while the JK unmelteds are due to the inability of the lower temperature of JK flame to melt the larger particles. SEM micrographs of the unmelted particles in the plasma and Jet Kote cavitated coatings are shown in Figure 14.

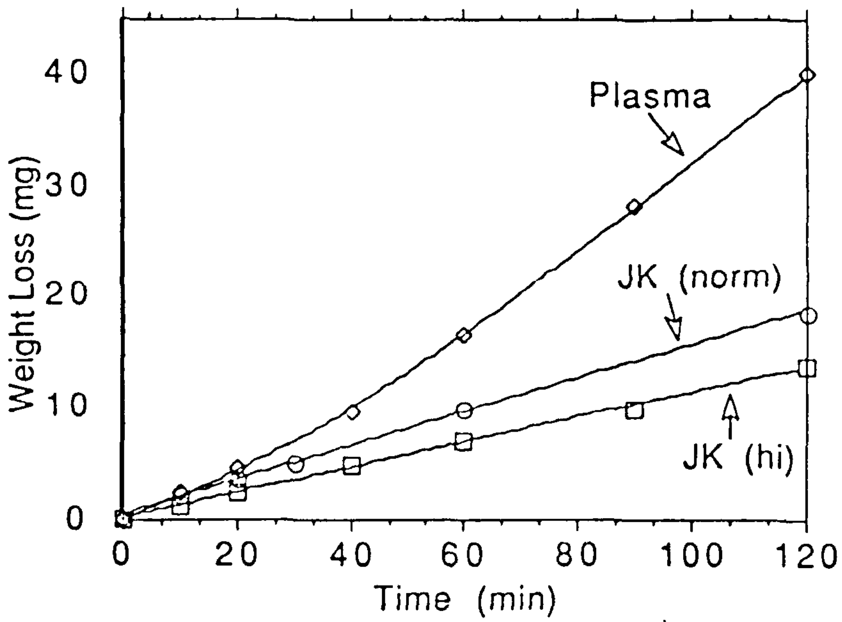

Figure 12. Cavitation-erosion data for aluminum-bronze coatings sprayed by plasma and Jet Kote. The Jet Kote coatings were sprayed at two parameter sets; normal gas flows and with high oxygen and fuel flows.

In an effort to determine the effects of the unmelted particles on the coatings properties and to attempt to produce superior coatings, a finer powder cut will be obtained to produce the next series of coatings.

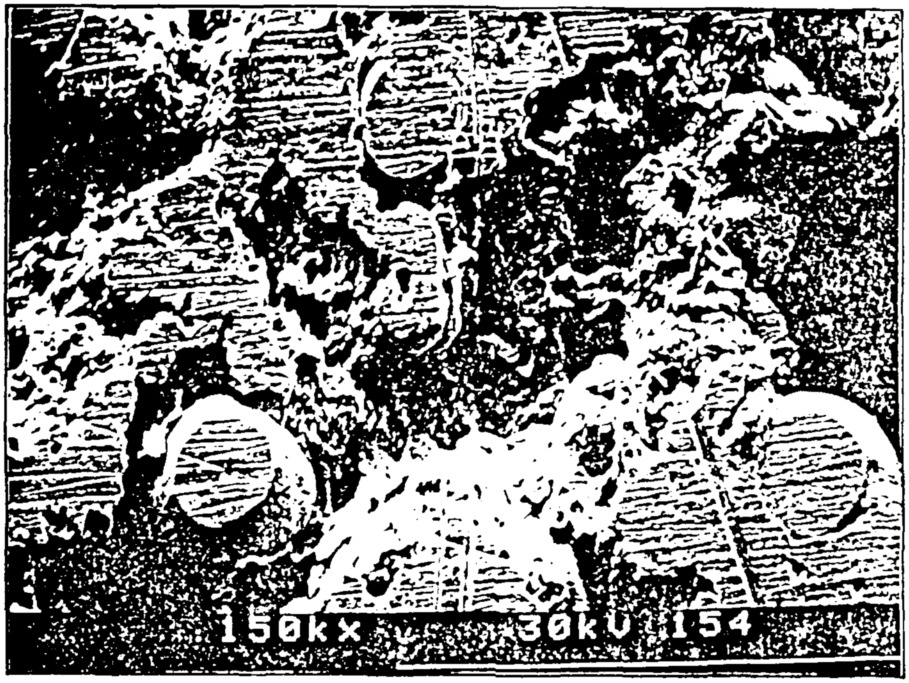

Figure 13a) SEM micrograph of the surface of the normal parameter Jet Kote al-bronze coating after cavitation for 120 minutes (150x). Note the large unmelted particles.

Figure 13b) SEM micrograph of the surface of the plasma sprayed al-bronze coating after cavitation for 120 minutes (150x). Fully melted platelets and some entrapped unmelted particles are evident.

Figure 14a) SEM micrograph of the surface of the normal parameter Jet Kote al-bronze coating after cavitation for 120 minutes (300x). Large unmelted and smaller partially melted particles are evident, along with fully melted spiats.

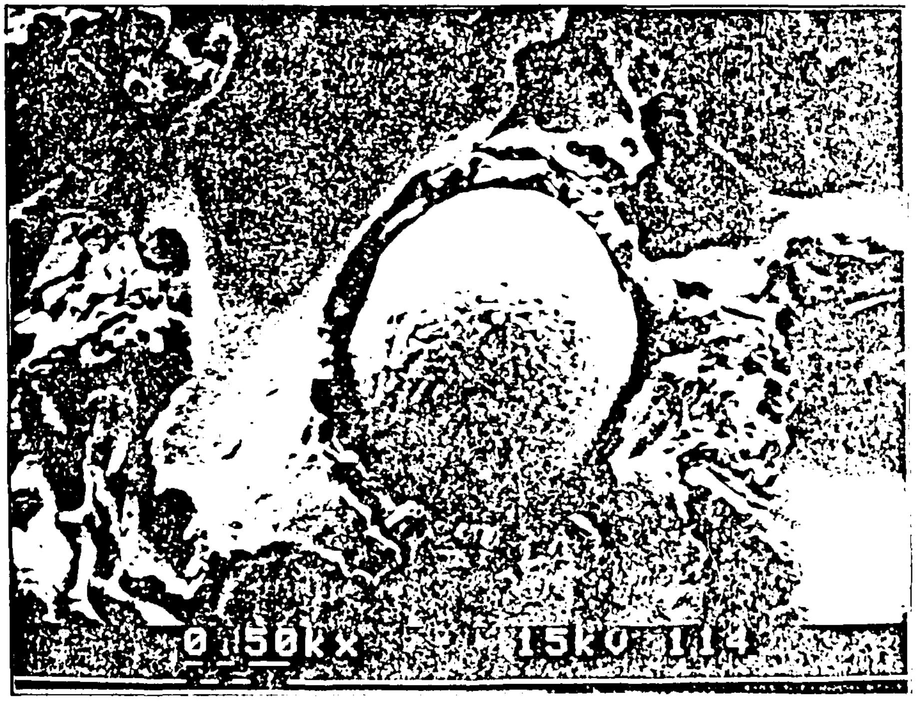

Figure 14b) SEM micrograph of the surface of the plasma sprayed al-bronze coating after cavitation for 120 minutes (500x). Note the unmelted particle entraped by the laminar platelets.

A DJ aluminum-bronze coating was produced using Metco's standard parameters and Diamalloy 1004 powder. Despite the smaller size of the Metco powder, -53 +15μm, a coating similar to that produced by Jet Kote was obtained. This coating also has a large number of unmelted particles, the difference being that the DJ unmelted are much smaller than the JK unmelteds, 40 μm compared to 120 μm. The DJ coating is more cavitation erosion resistance than the plasma sprayed coating, as shown in Figure 15.

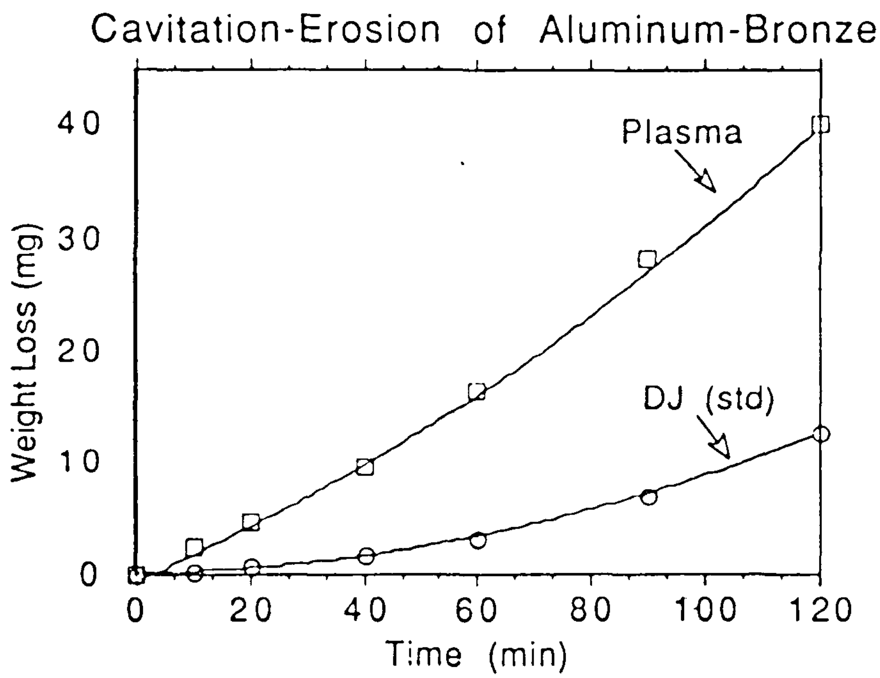

Figure 15. Cavitation erosion behavior of aluminum-bronze coatings sprayed with Diamond Jet and plasma.

Metco 143 powder is an unalloyed mixture of zirconia, titania, and yttria; 72-18-10 weight percent, respectively. The diffraction pattern of the feedstock powder indicates the presence of ZrO_2 monoclinic phase, and cubic Y_2O_3. After plasma spraying, a dramatic

change is seen in the diffraction pattern, Figure 16. The three phases transform almost completely to a single FCC phase with a lattice parameter similar to that of the cubic zirconia phase. The fact that the as-sprayed structure is far less complex than that of the starting powder is very unusual. There is a difficulty in obtaining an HVOF coating of 143 in that Metco is the only supplier of the powder and it is only available in a rather coarse cut of -75 +5 µm. Due to the high melting point of the material, 2535°C, a finer powder cut must be obtained before a coating can be produced. We are currently discussing the possibility of obtaining this powder of a better cut with other suppliers.

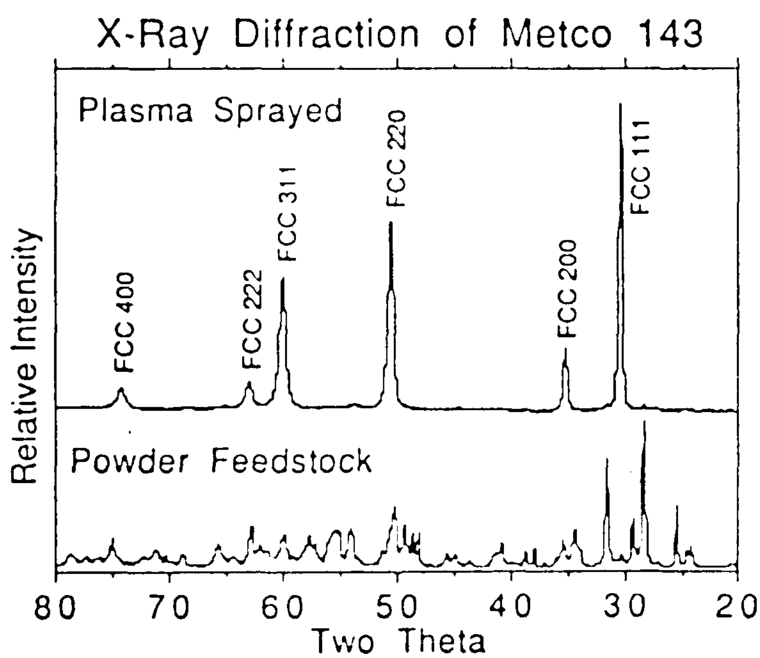

Figure 16. X-ray diffraction pattern of Metco 143 powder and plasma sprayed coating. The powder contains ZrO_2, TiO_2, and Y_2O_3. The coating is primarily single phase FCC with small amounts of ZrO_2 and TiO_2

In addition to the work reported above, SEM and X-ray diffraction analysis has been performed on all of the powders. The

results are not as meaningful unless they are compared with the coatings which are produced from the powders; therefore, these results are not presented in this interim report.

Conclusion

To-date, coatings have been produced with the three HVOF systems currently available commercially, Jet Kote, Diamond Jet, and CDS. Conventional plasma and electric arc (when appropriate) coatings have also been produced as a basis of comparison to the HVOF coatings. Powder sources have been obtained for all of the required materials, and powder analysis has been conducted on these powders. The parameters for each test have been established, and coating analysis and mechanical testing have been initiated on the coatings.

Future work

Considerable work remains to be carried out on the testing matrix of all of the materials on all of the systems, with coating optimization to be performed as required.

During the Summer of 1990, R. Greenlaw, Graduate Research Assistant, will go to Bender Machine in Vernon, California to continue the Jet Kote spraying tests. Bender is equipped with the newer JK 2000 Series Gun, as compared to the older 1000 Series Gun at Stony Brook. It is believed that conducting the spraying with the newer gun will provide results more representative of the Jet Kote units presently on the market.

Mr. Jack Ritchie, President of Bender Machine, has offered to sponsor Mr. Greenlaw during the entire summer in order that the

Jet Kote, as well as a recently installed Miller Top Gun, can be evaluated.

. It should be noted that David Lee, Coatings Engineer at Stellite Coatings, visited Stony Brook in March and was satisfied with the condition of the Jet Kote system at the Thermal Spray Laboratory.

The evaluation of the Diamond Jet System has up to this point been conducted at Metco-Perkin Elmer in Westbury, N.Y. While some of the future work will also be carried out at Metco DJ spraying will also be studied by Mr. Greenlaw at the David Taylor Naval Ship Research and Development Center at Annapolis.

The evaluation of CDS has and will continue to be carried out at Flame Spray Industries in Port Washington, N.Y.

Only preliminary results are currently presented. It is clear, however, that HVOF will have a significant impact on the thermal spray industry. In fact in examining the current date, HVOF displayed dramatic performance when compared to the plasma and electric arc (wire) sprayed coatings. The present researchers enthusiastically continue this program of evaluation.

Please note that this proposal for continuation is currently being prepared for the next contract period (1 July 1990 - 30 June 1991).

A milestone chart is presented in Figure 17.

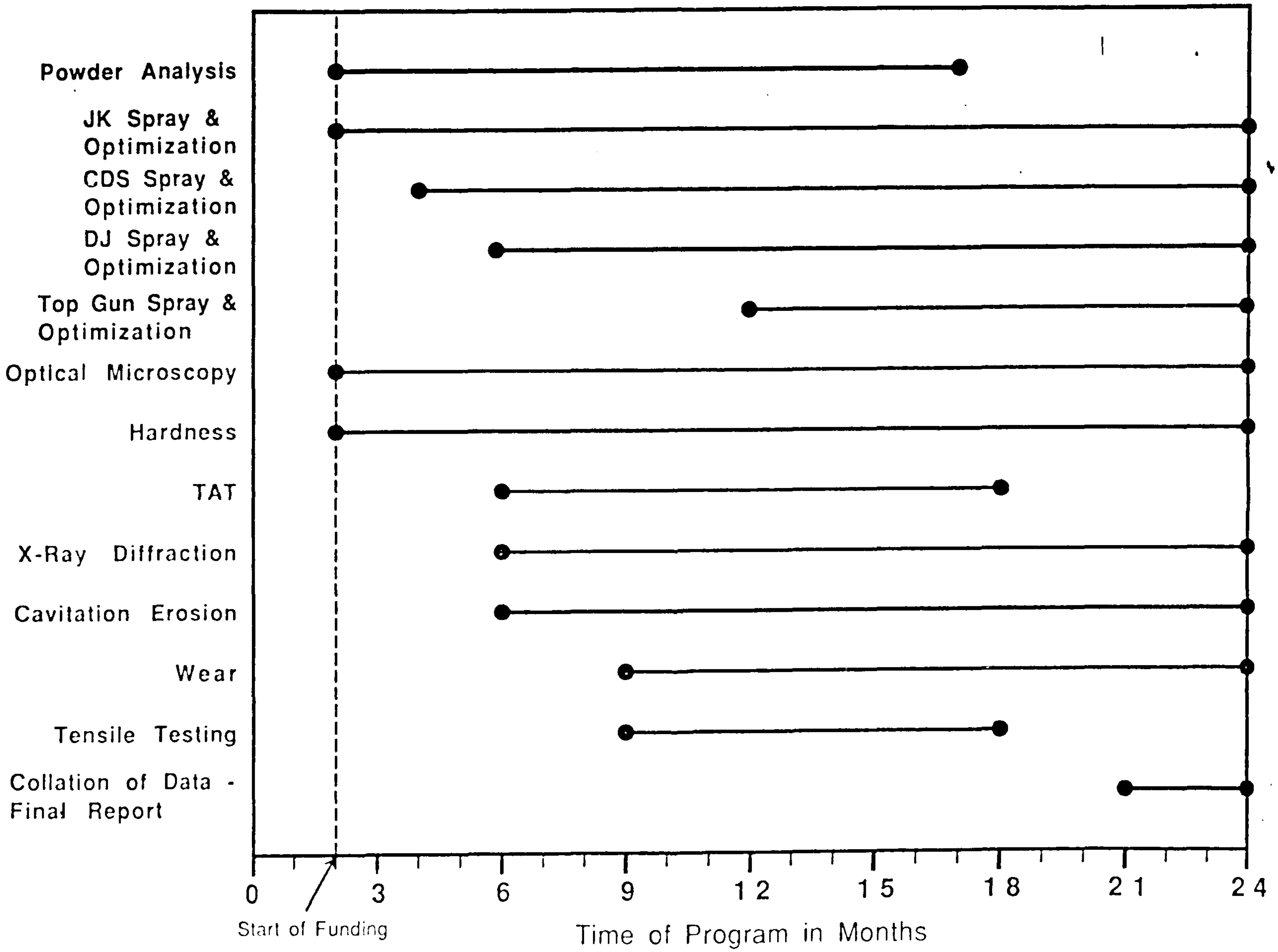

Figure 17. Milestone Chart